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A Rugged, Low-Cost Diode Laser Sensor for H_2O and Temperature

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Outline

- Motivation
- System Design
- Outline of Theory
- Calibration
- Results from a Flat Flame
- Conclusions & Future Work

Motivation

- Improved energy efficiency is needed for Industries of the Future (IOF) to stay globally competitive
- Future emissions regulations will require closer monitoring of industrial combustors
- *In situ* sensors for active control are scarce
- Accurate, robust, and inexpensive sensors are needed for industrial combustion monitoring

Objective

To build and test a Tunable Diode Laser Absorption Spectroscopy (TDLAS) system to measure real-time concentrations and temperatures non-intrusively in industrial burners

Scope

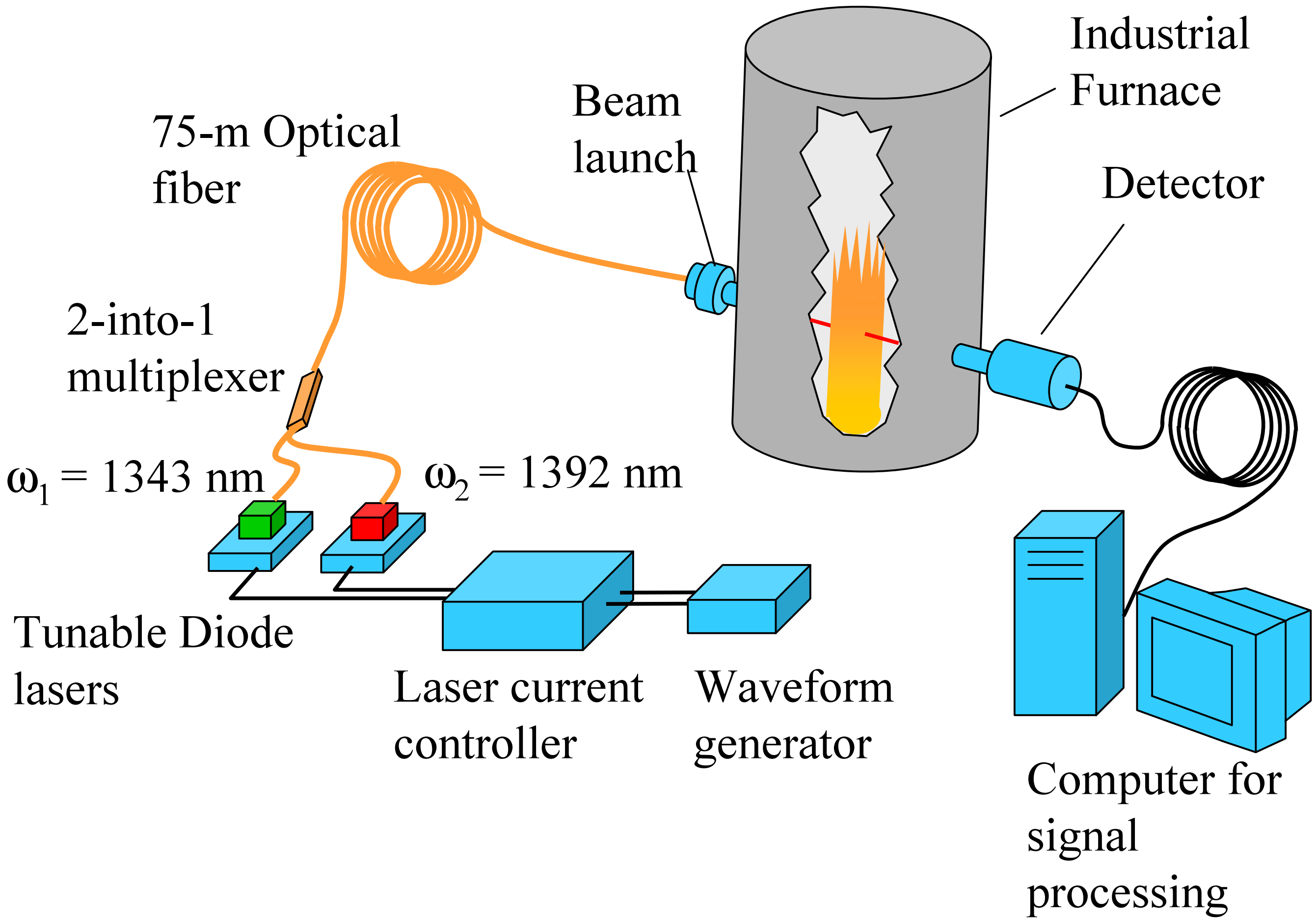
✓ • Design and build a robust diode laser system to withstand the harsh environments of industrial applications

✓ • Calibrate and test the system in a laboratory

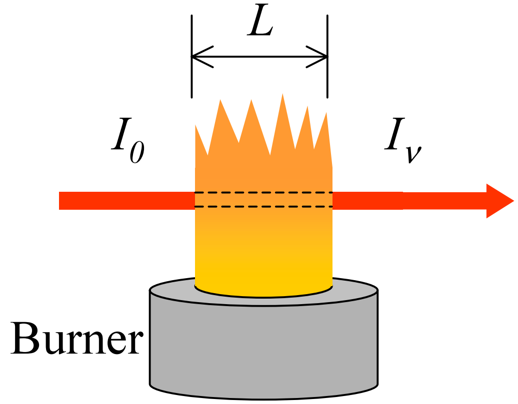
• Integrate the system into an industrial burner

• Test the system in real-world conditions

TDLAS System for Monitoring Temperature and H_2O in Industrial Burners



Theory of Mole Fraction (X_i) Measurements:
Scanned Wavelength Absorption Spectroscopy



Beer-Lambert relation:

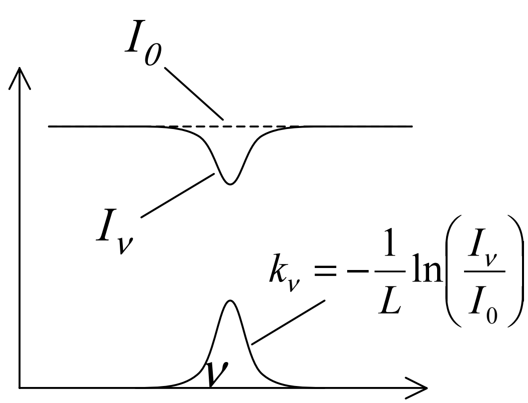
$$\frac{I_\nu}{I_0} = \exp(-k_\nu L)$$

For line j of species i:

$$k_\nu = P X_i S_j \phi_j$$

Where: $S_j = S_j(T)$

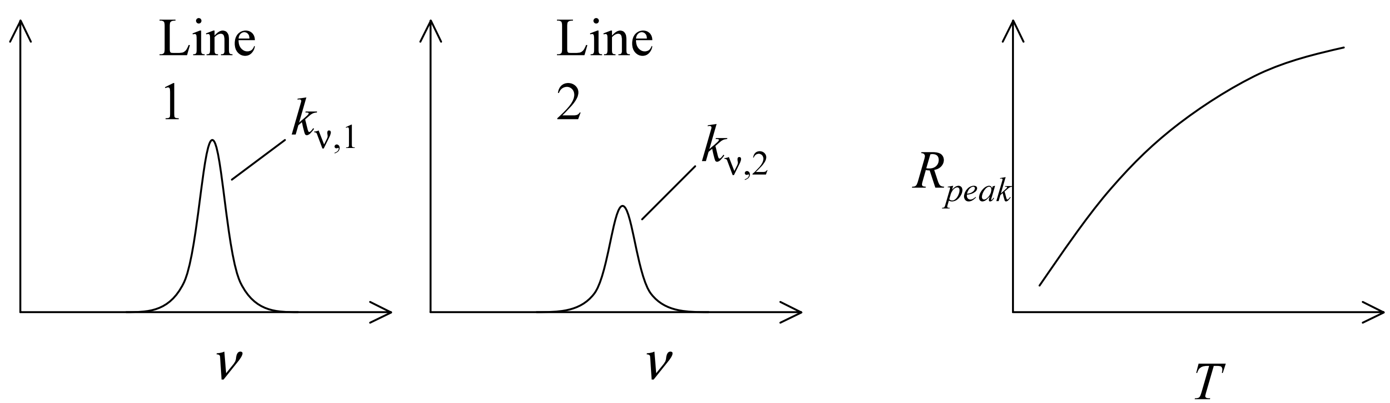
$$\phi_j = \phi_j(\nu)$$



Measured $k_{\nu,\mathrm{peak}}$ yields X_i from:

$$X_i = \frac{k_{\nu,peak}}{P S_j \phi_j}$$

Theory of Temperature (T) Measurements:
Two-line absorption ratio technique



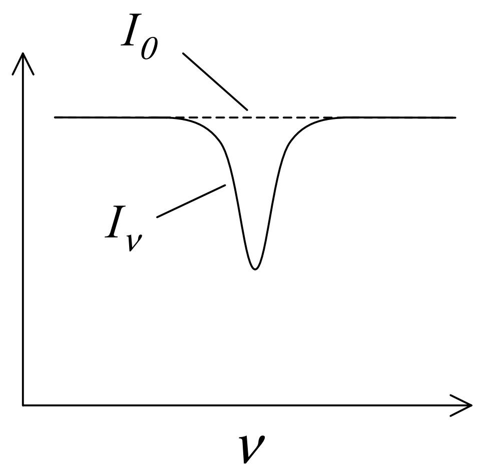
Ratio of peak absorbances:

$$R_{peak} = \frac{\left(k_{\nu,1}\right)_{peak}}{\left(k_{\nu,2}\right)_{peak}} = \frac{S_1(T_0)\phi_1}{S_2(T_0)\phi_2} \exp\left[-\frac{hc}{k}\left(E_1'' - E_2''\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

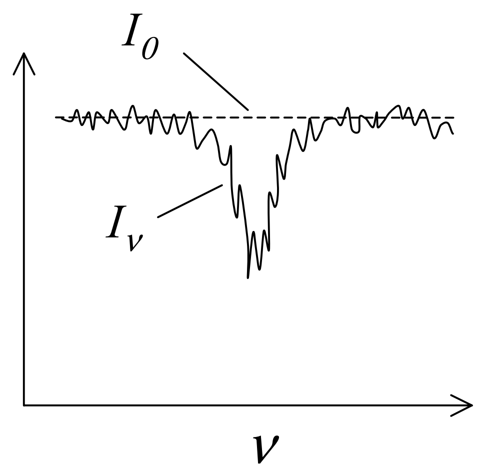
Measured R_{peak} is sensitive primarily to T only.

Practical Issues: Noise

Ideal:



Real:



Noise sources:

- Flame emission
- Laser amplitude noise
- Detector noise
- Amplifier noise

Noise reduction techniques:

- Balanced detection
- Frequency shifting with lock-in detection

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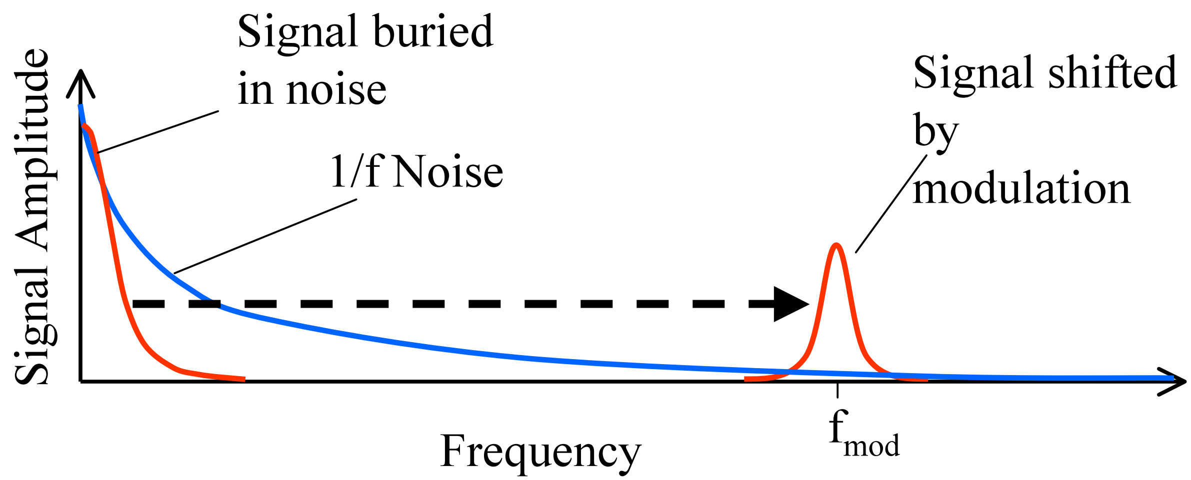
Noise Reduction by Modulation & Phase Detection: Shifting in Frequency Space



Lock-in detection method:

- Signal is frequency-shifted by modulating laser at f_{mod}
- Modulated signal is detected by a phase-sensitive method
- Noise is not modulated, thus is greatly reduced at f_{mod}

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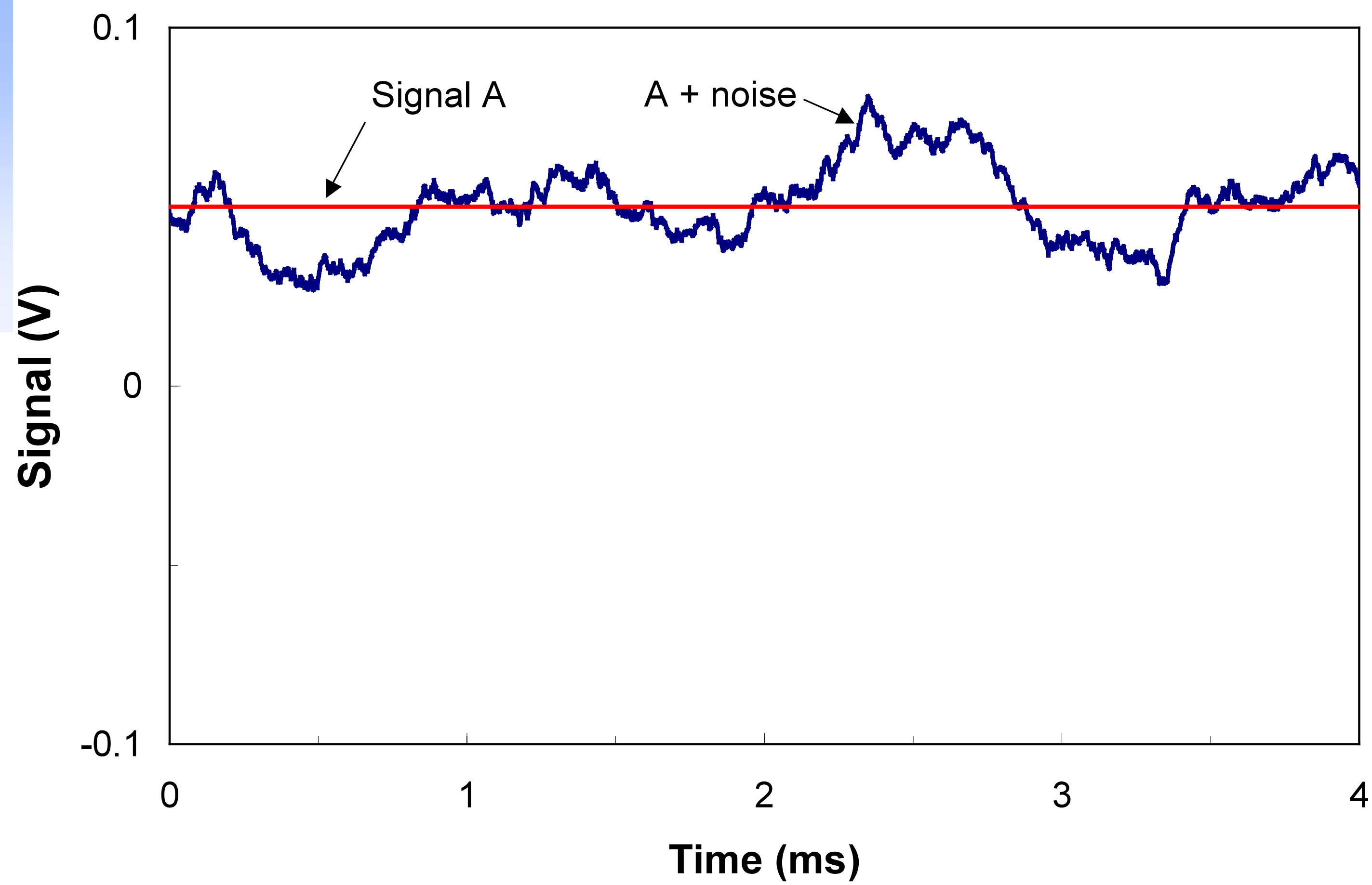
Example of Lock-in Detection



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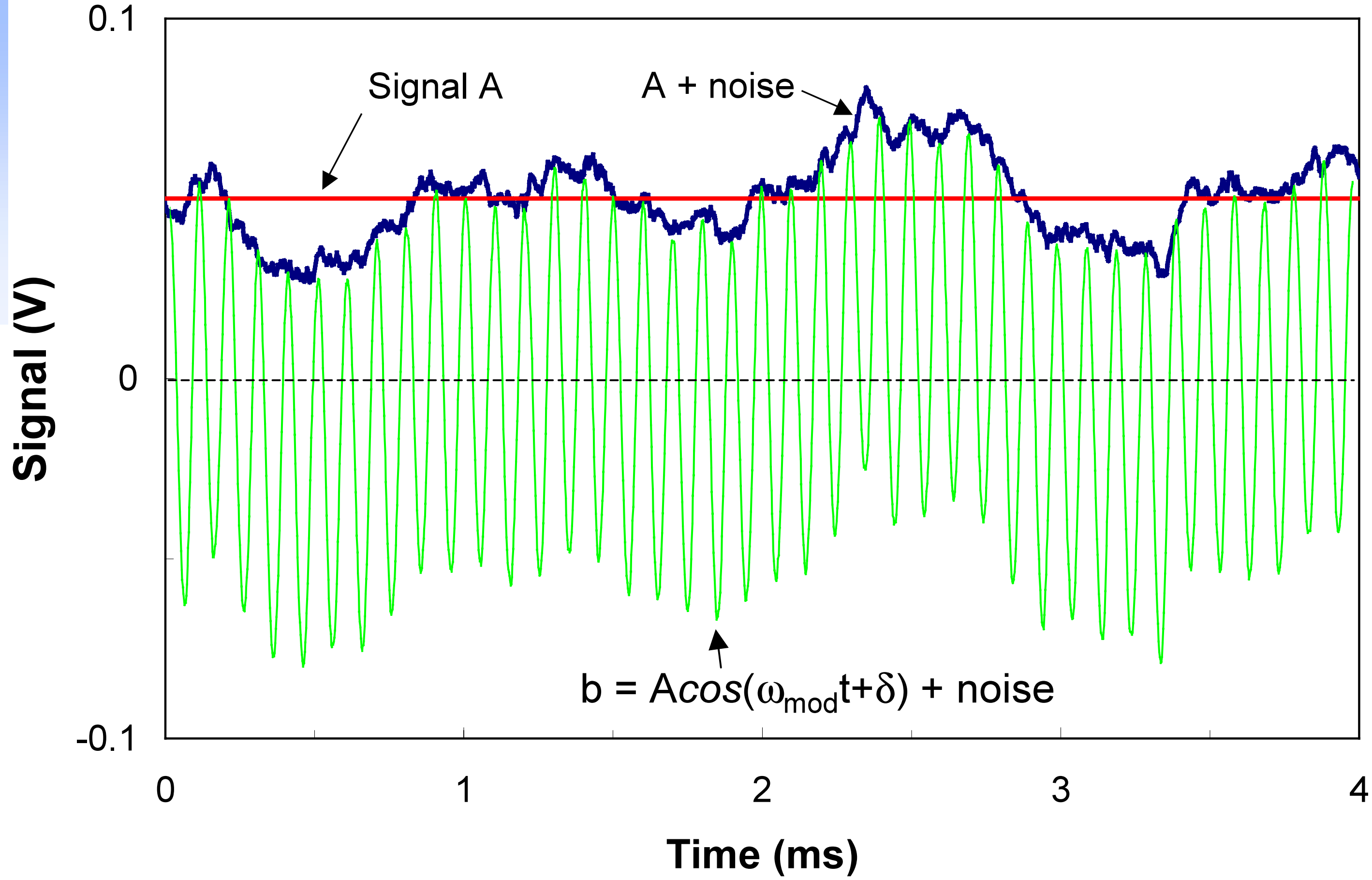
Example of Lock-in Detection

Signal A is Modulated to get Signal b

$\omega_{mod} >> \omega_A$



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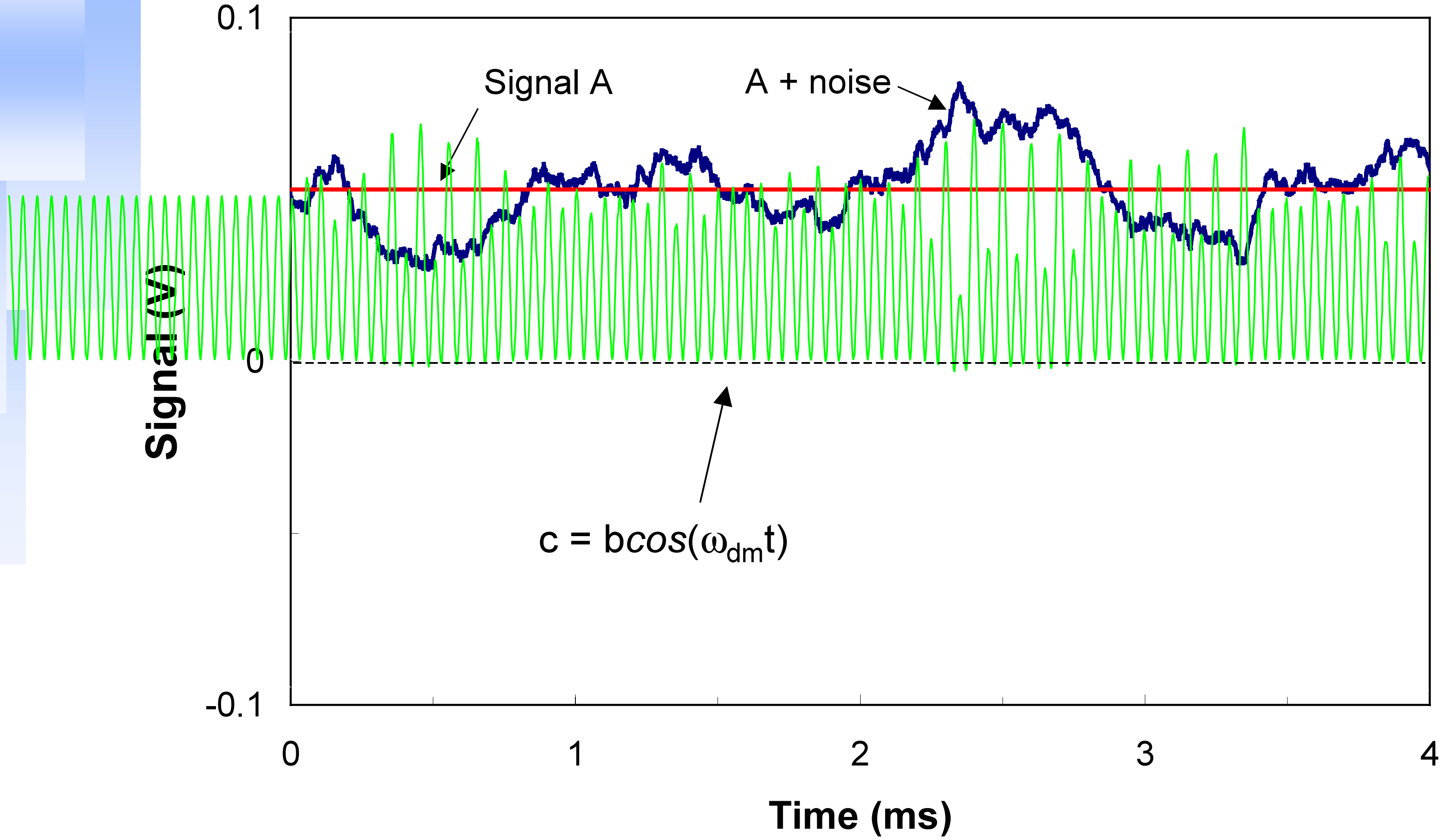
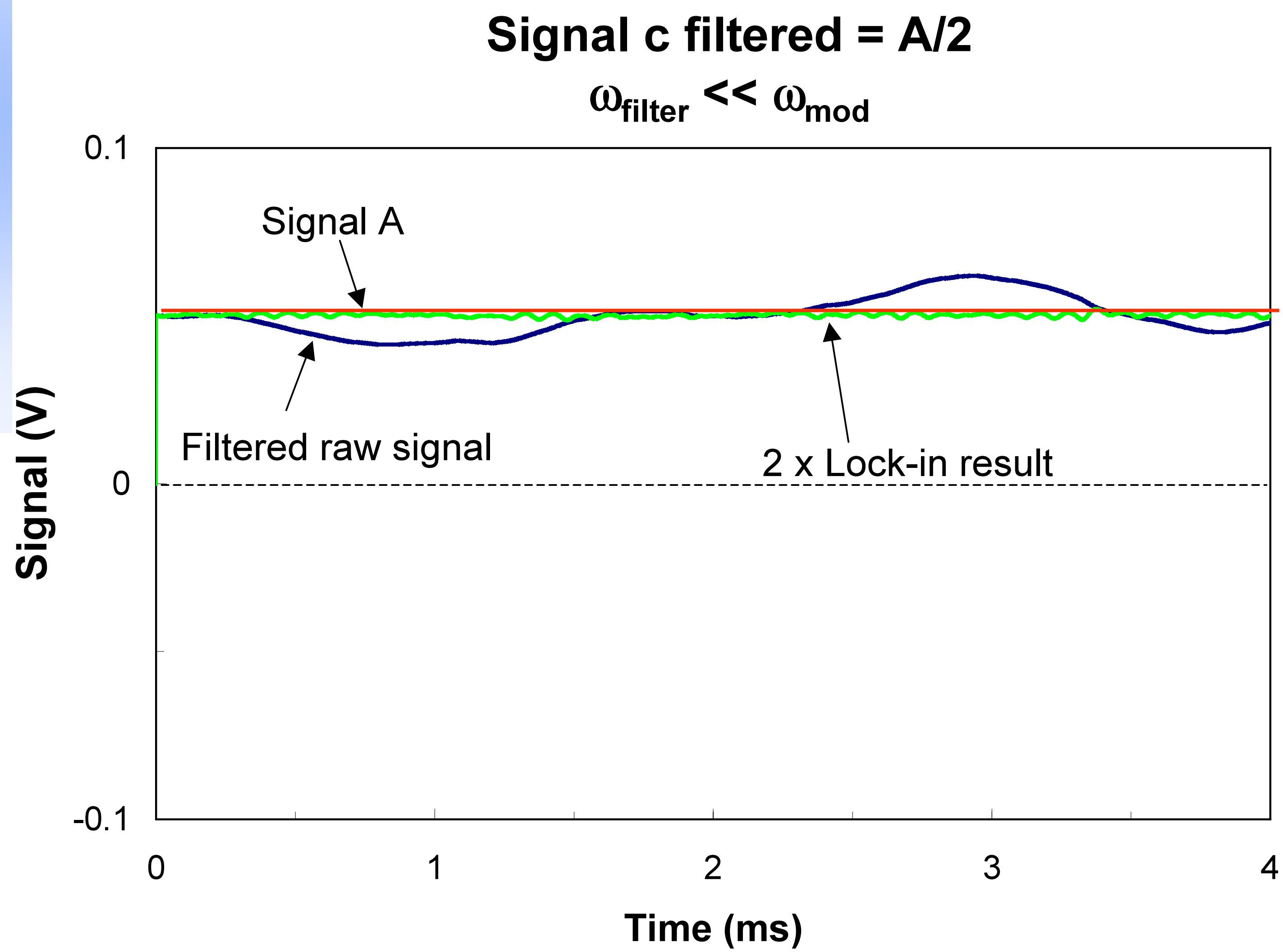
Example of Lock-in Detection

Signal b is multiplied by $cos(\omega_{dm}t)$ to get signal c

$\omega_{dm} = n\omega_{mod}$



Example of Lock-in Detection



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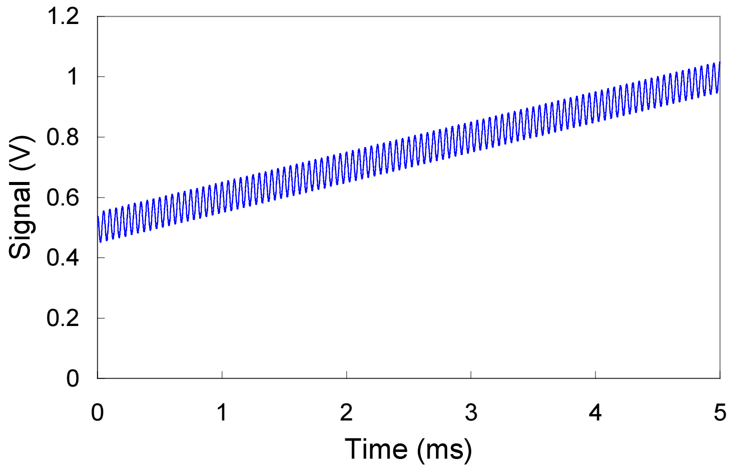
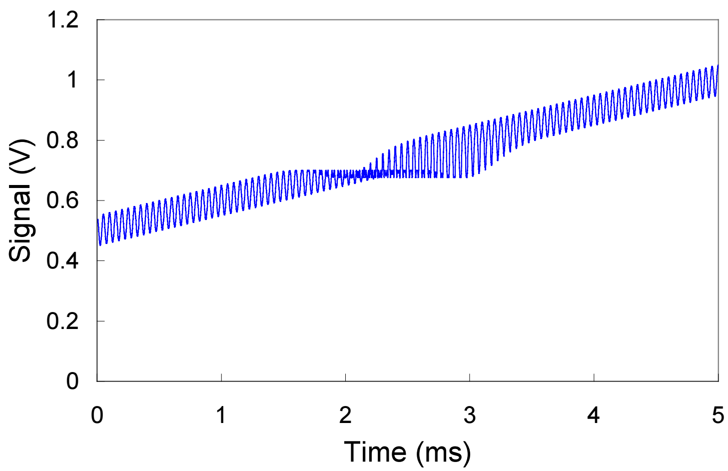
Wavelength Modulation Spectroscopy

Lock-in detection applied to an absorption scan



Scan Waveform:

- High-freq. Modulation enables lock-in detection for noise reduction
- Current ramp produces laser wavelength scan

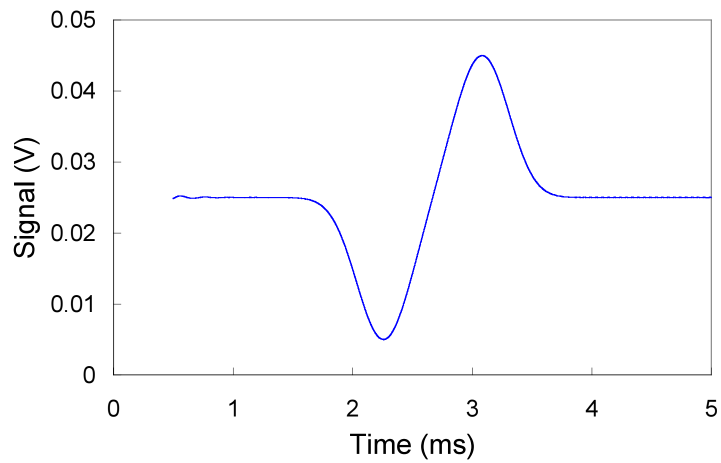


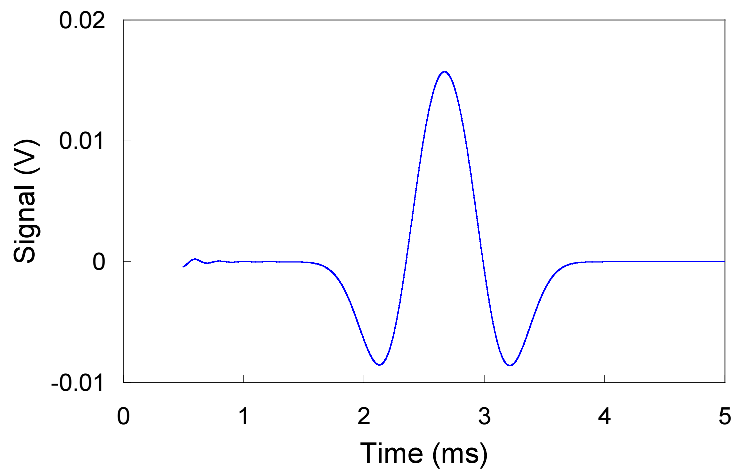
Waveform with absorbance:

- Absorption modifies waveform
- Lock-in signal is sensitive to absorption

Wavelength Modulation Spectroscopy

Lock-in detection applied to an absorption scan





<u>1*f* Waveform</u>:

- $\omega_{dm} = \omega_{mod}$
- Waveform resembles 1st derivative of lineshape

<u>2*f* Waveform</u>:

- $\omega_{dm} = 2\omega_{mod}$
- Waveform resembles 2nd derivative of lineshape
- 2*f* signal = 0 in the wings

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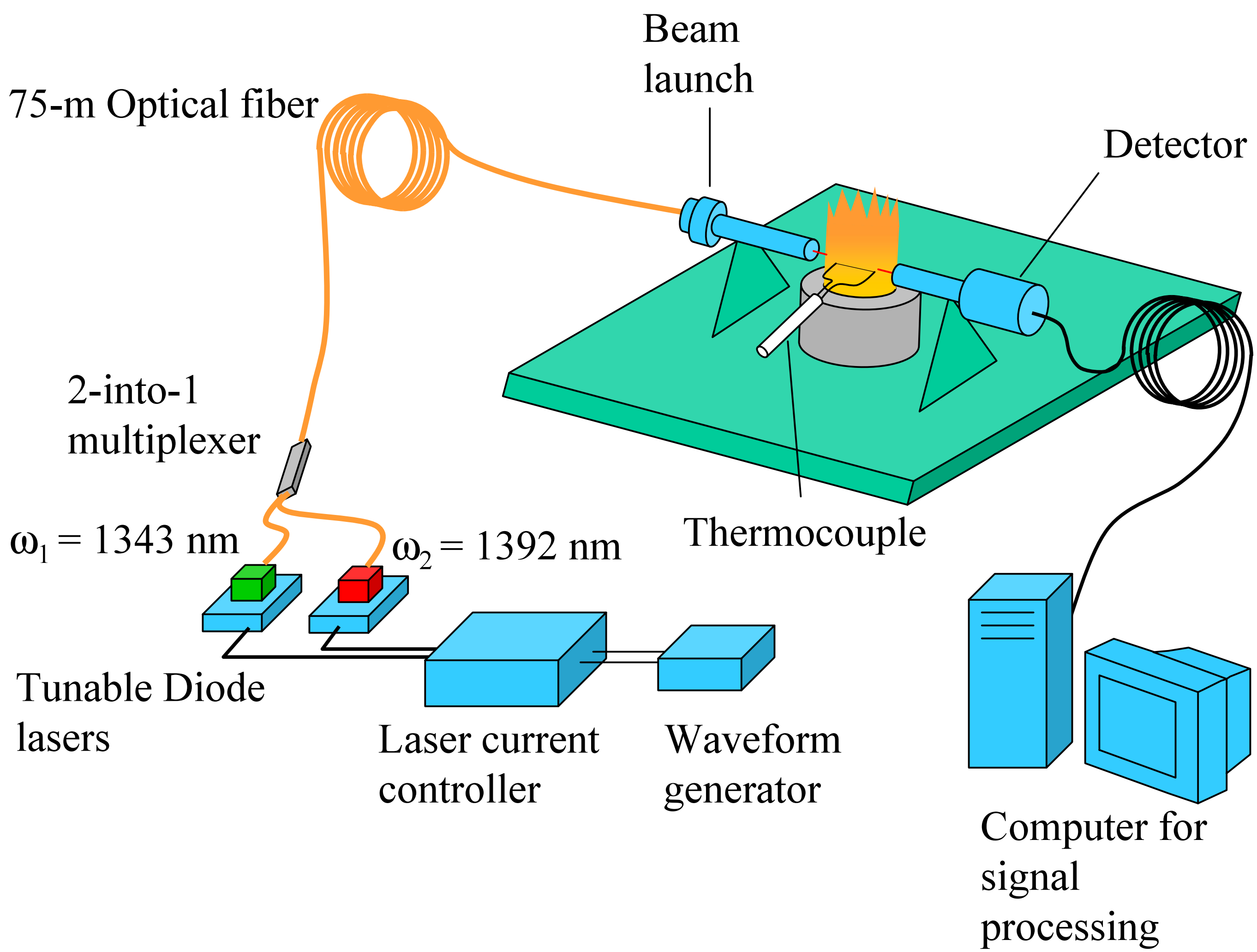
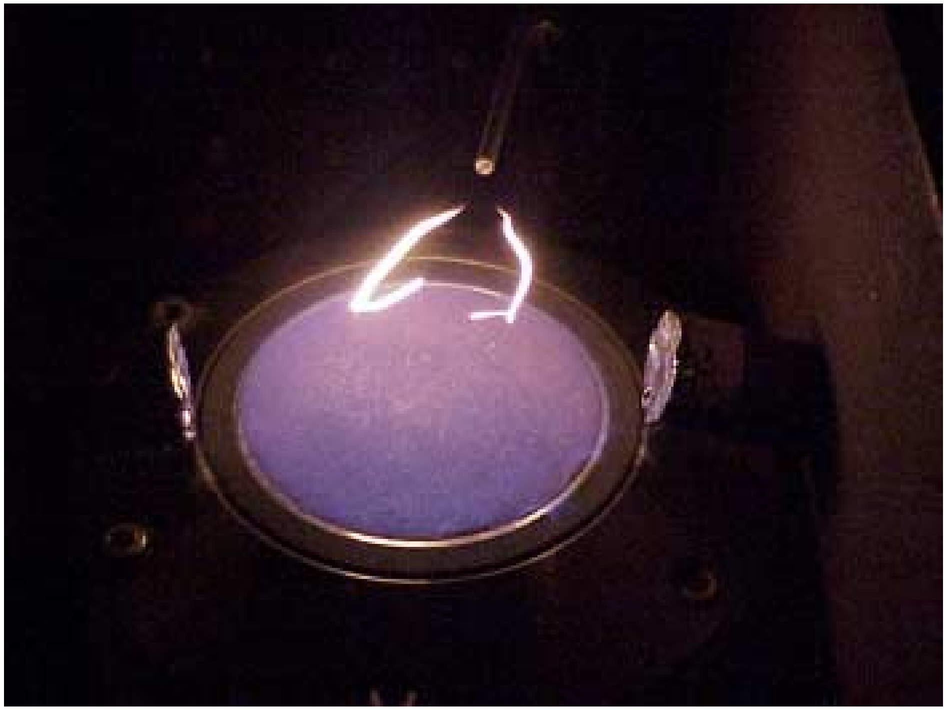
Calibration of TDLAS System

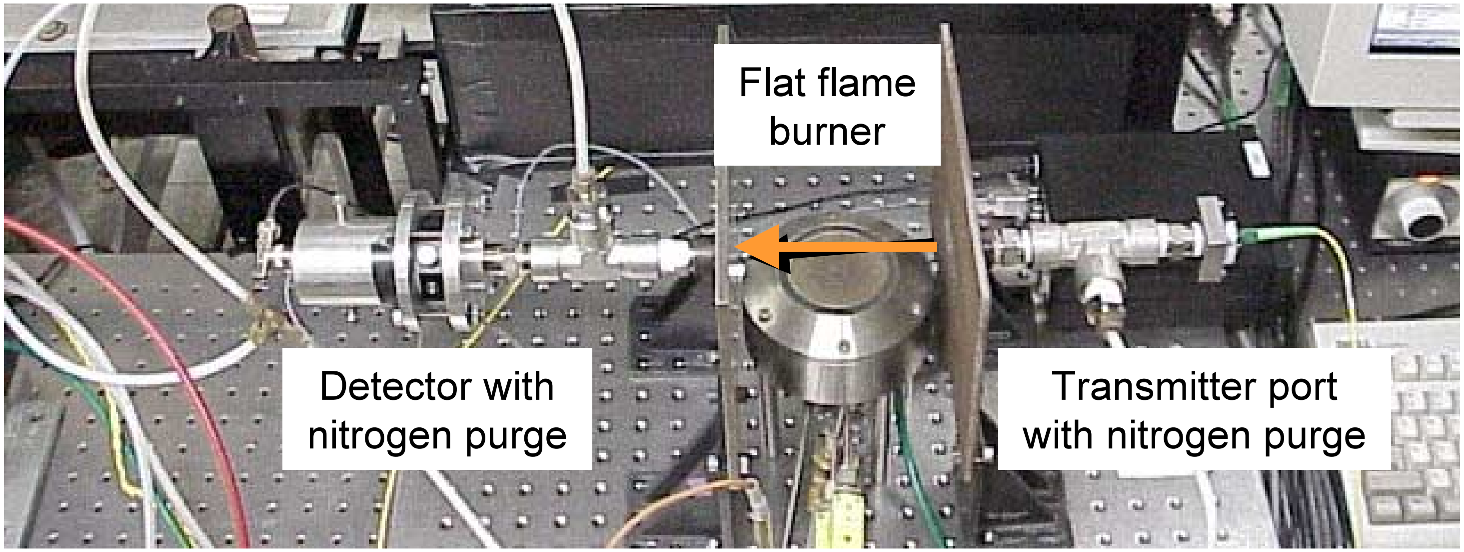


Failure of Thermocouple at High Temperature



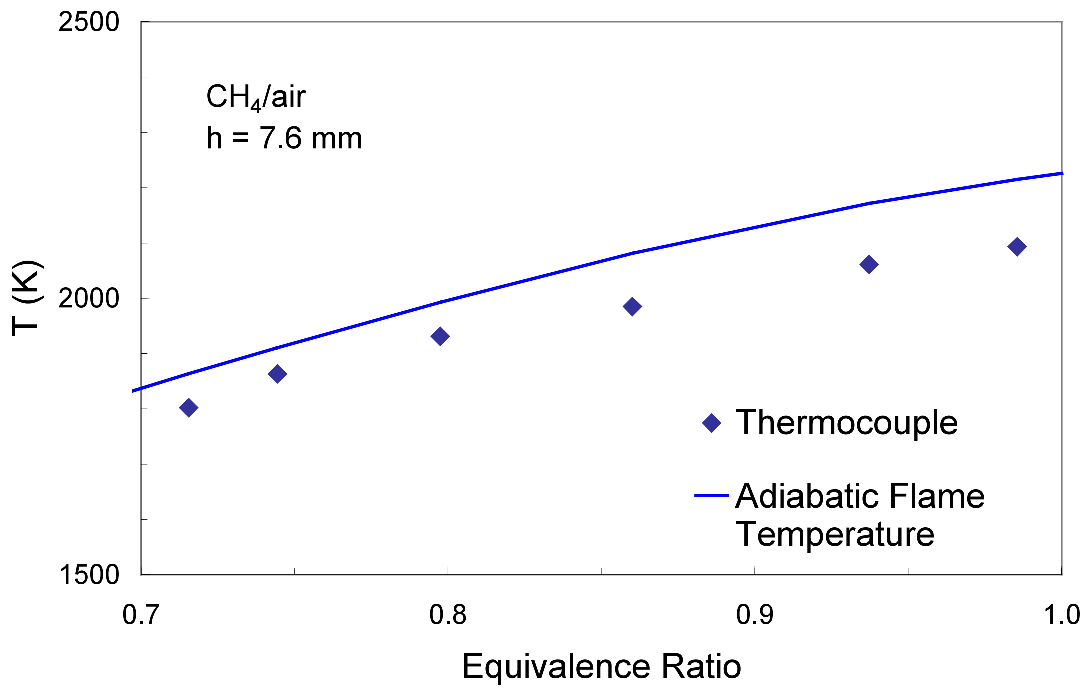
- S-type thermocouple fails during use at T > 2000 K
- Thermocouple life is significantly reduced for T > 1800 K

Detail of Interface Hardware



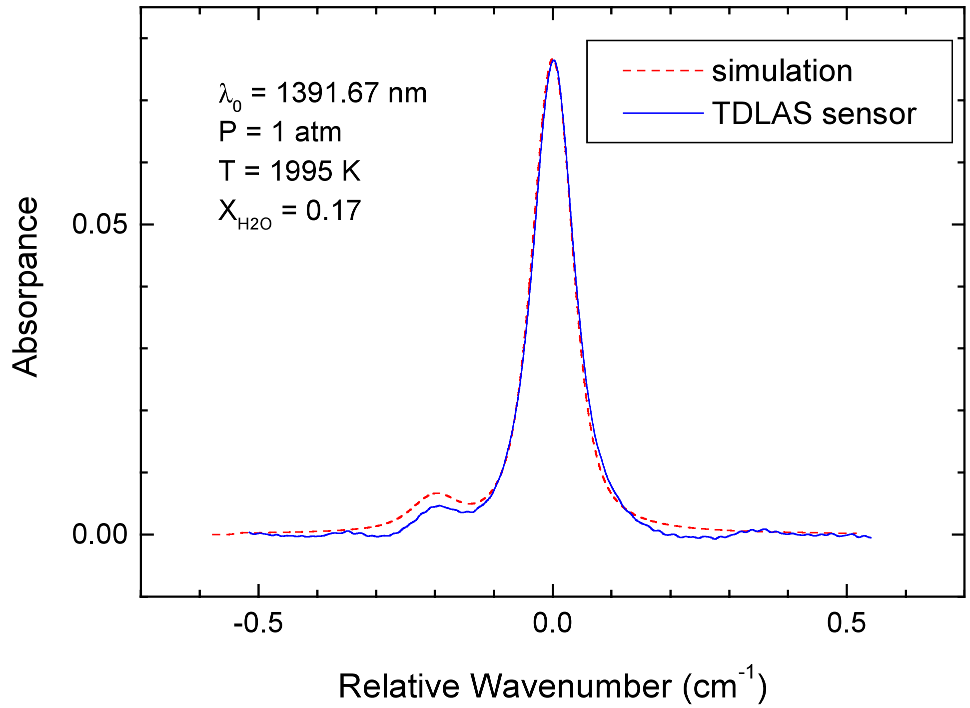
- Transmitter and detector mounted rigidly using pipe fittings
- Single detector simplifies the system

Characterization of Premixed Flat Flame



- Corrected thermocouple measurements in good agreement with thermochemical equilibrium calculations.
- Temperatures can be varied over 300 K while flame remains stable.

Example Scan in a CH_4/air Flat Flame



- Scanning range covers entire line
- Good agreement with simulation based on HITEMP database

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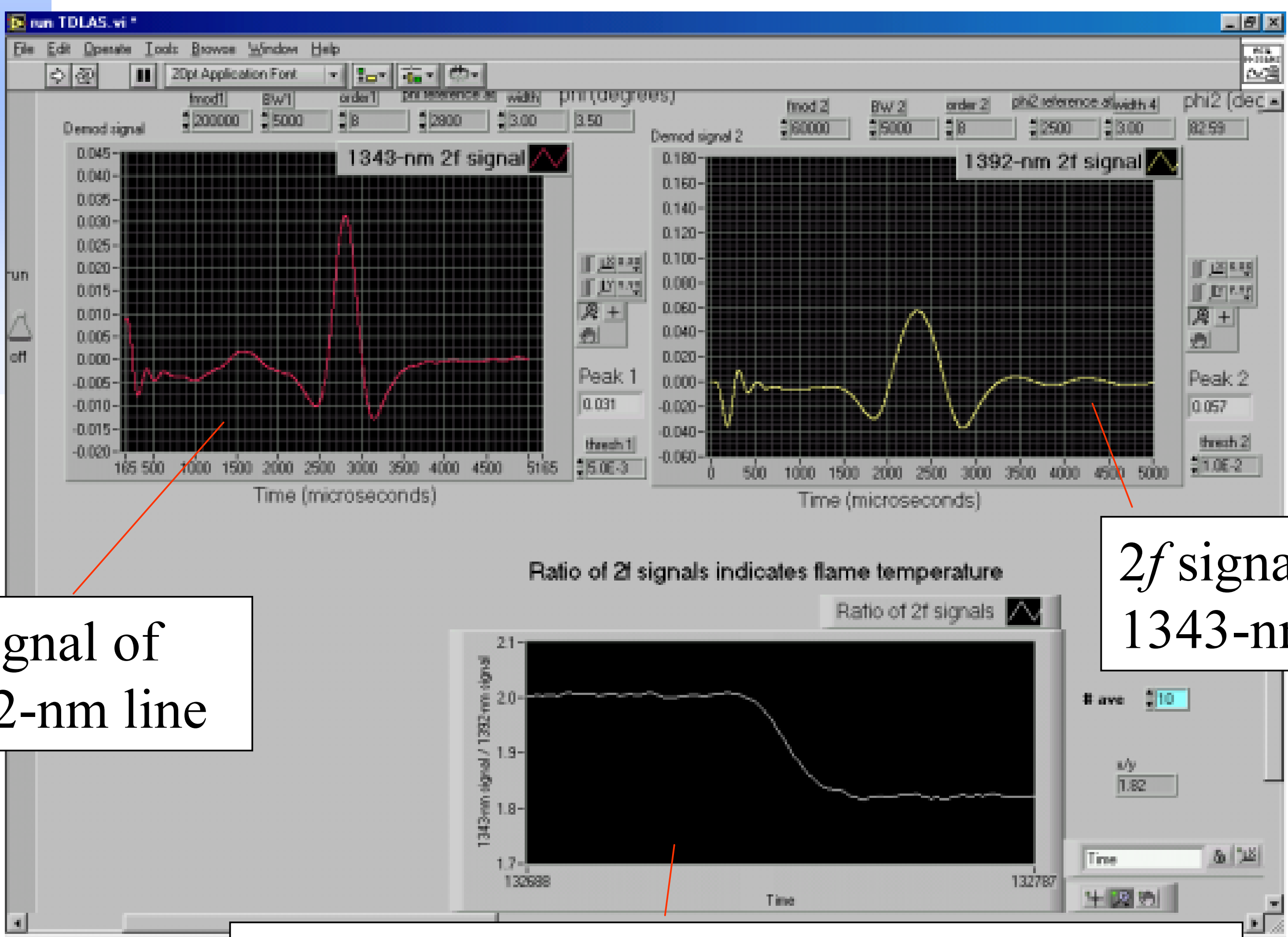
Signal Processing Program

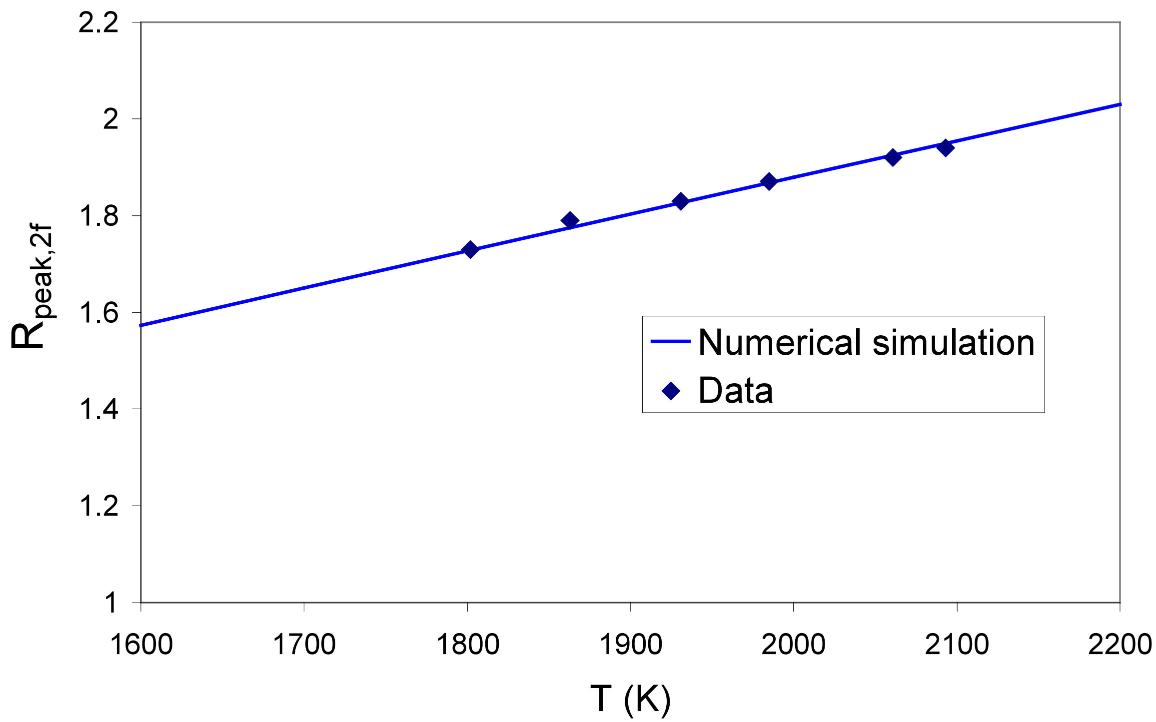


2*f* signal of 1392-nm line

2*f* signal of 1343-nm line

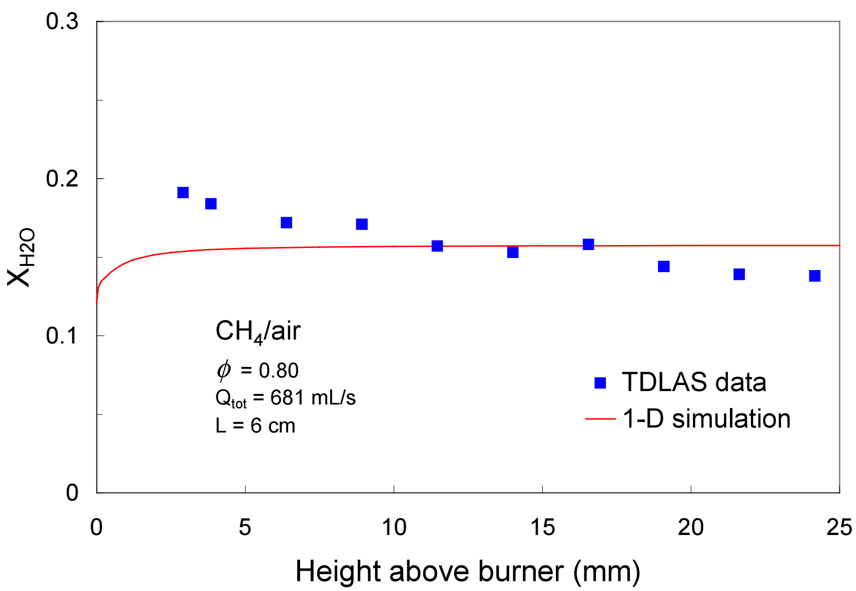
Real-time strip chart display of $R_{2f} \sim T$

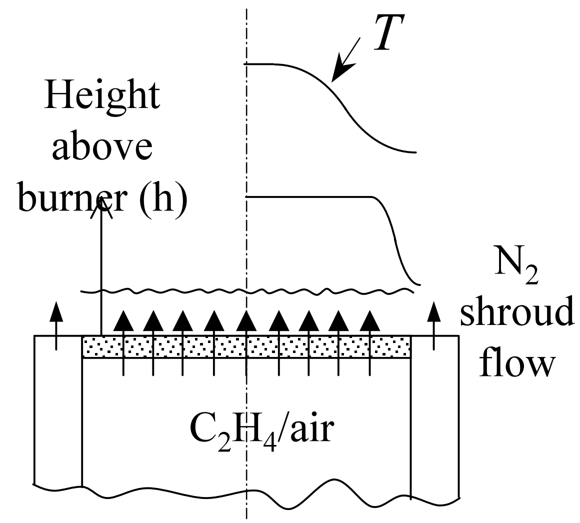
Calibration of 2*f* Ratio for Temperature



- Simulated 2*f* ratio anchored by thermocouple data, establishing a calibration

H_2O Profile in 1-D Flame Measured Using TDLAS





- Experimental mole fractions in good agreement with theoretical
- Measured X_{H2O} decreases with height due to mixing

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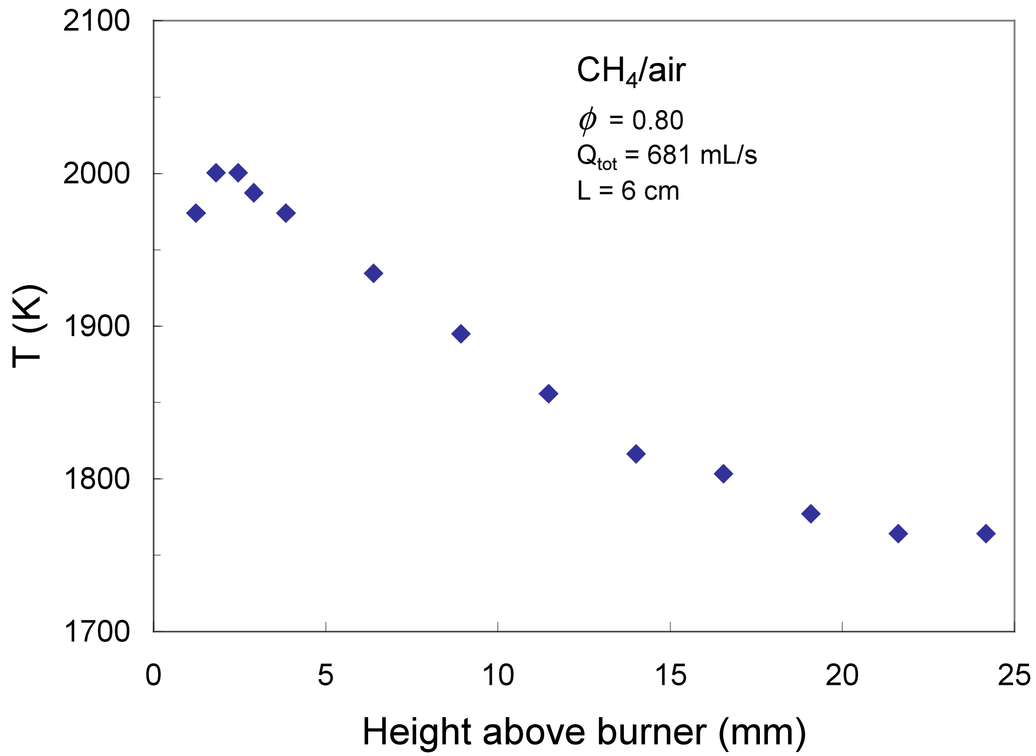
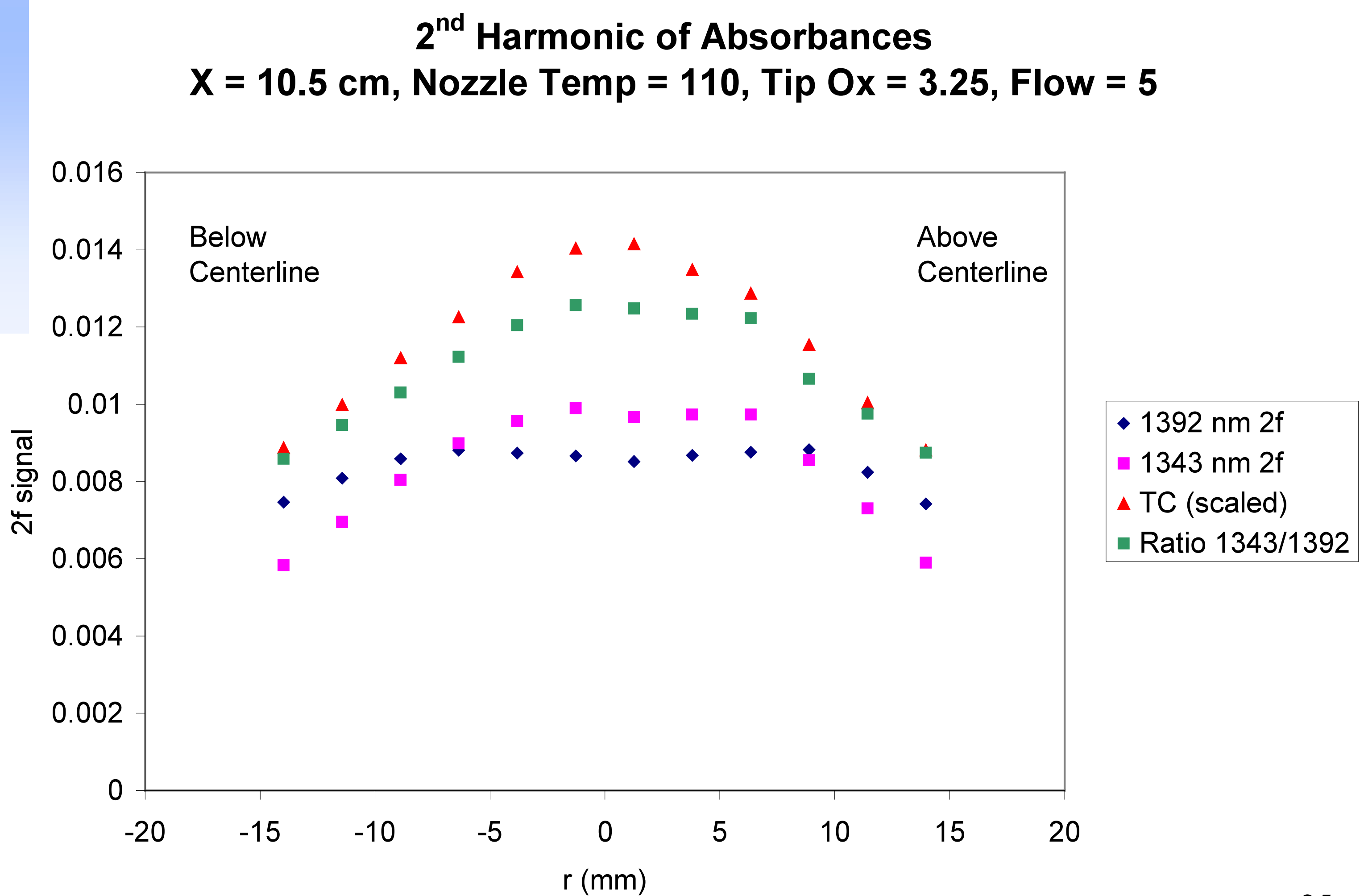
TDLAS Temperature Profile in 1-D Flame

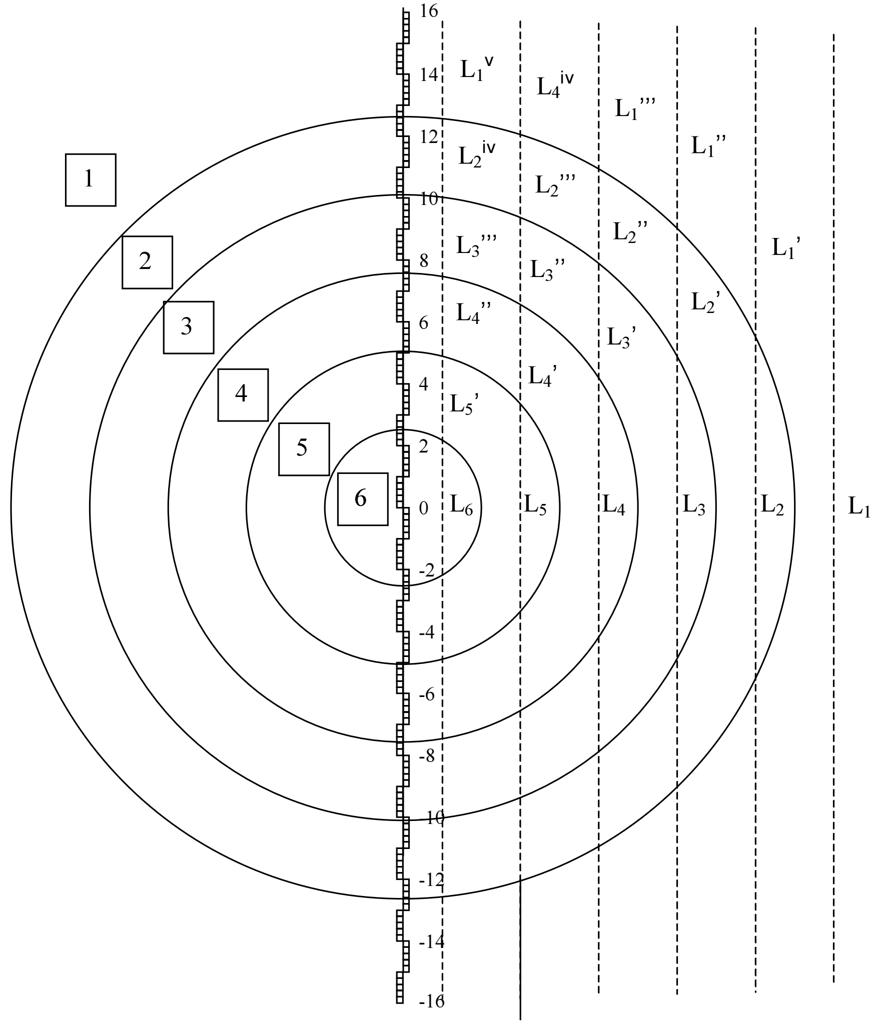


- Measurements made near the flame zone where thermocouples fail
- Data rate of 10 Hz surpasses thermocouple system by 20x

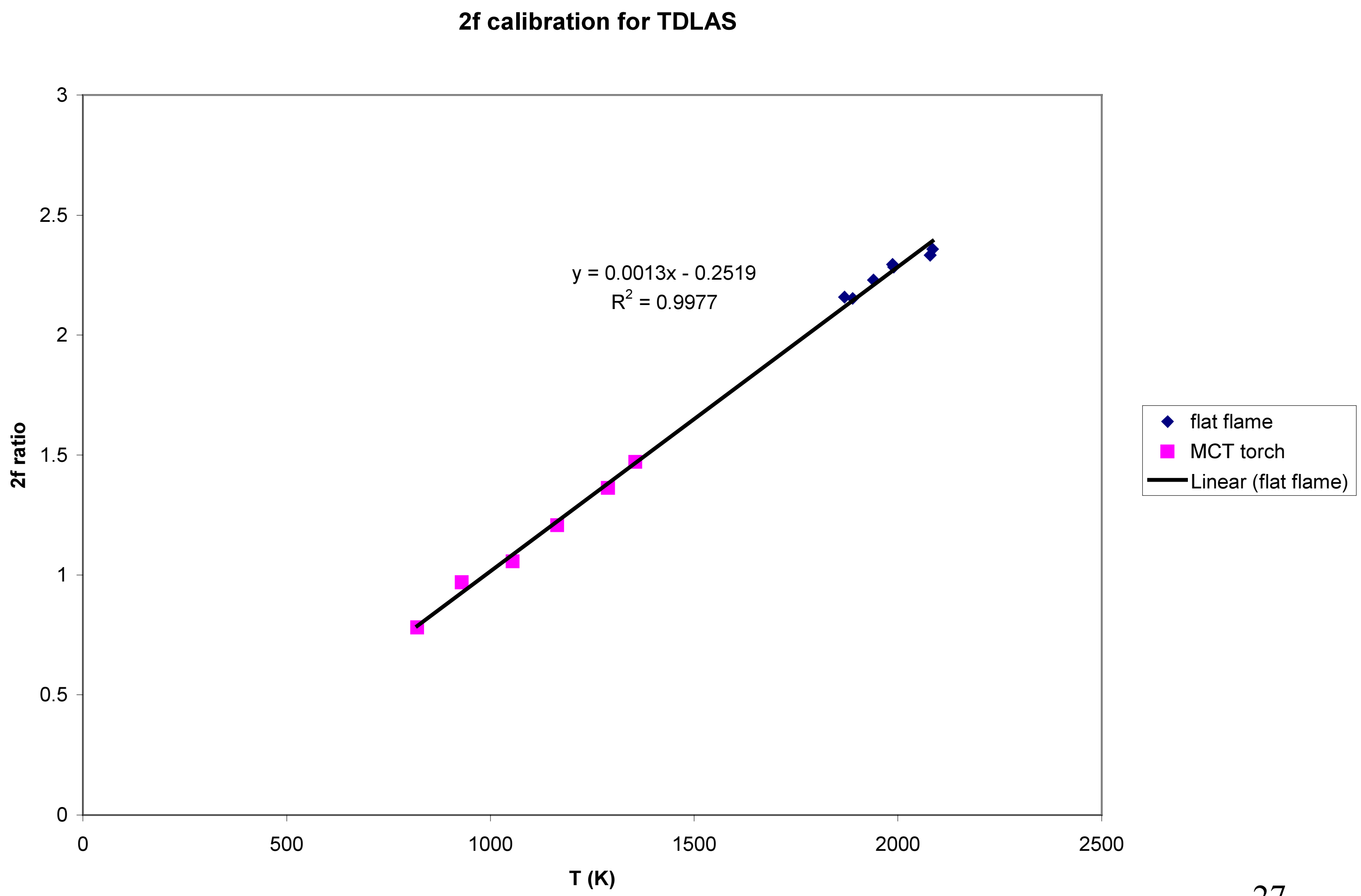
Raw Data: TDLAS and TC



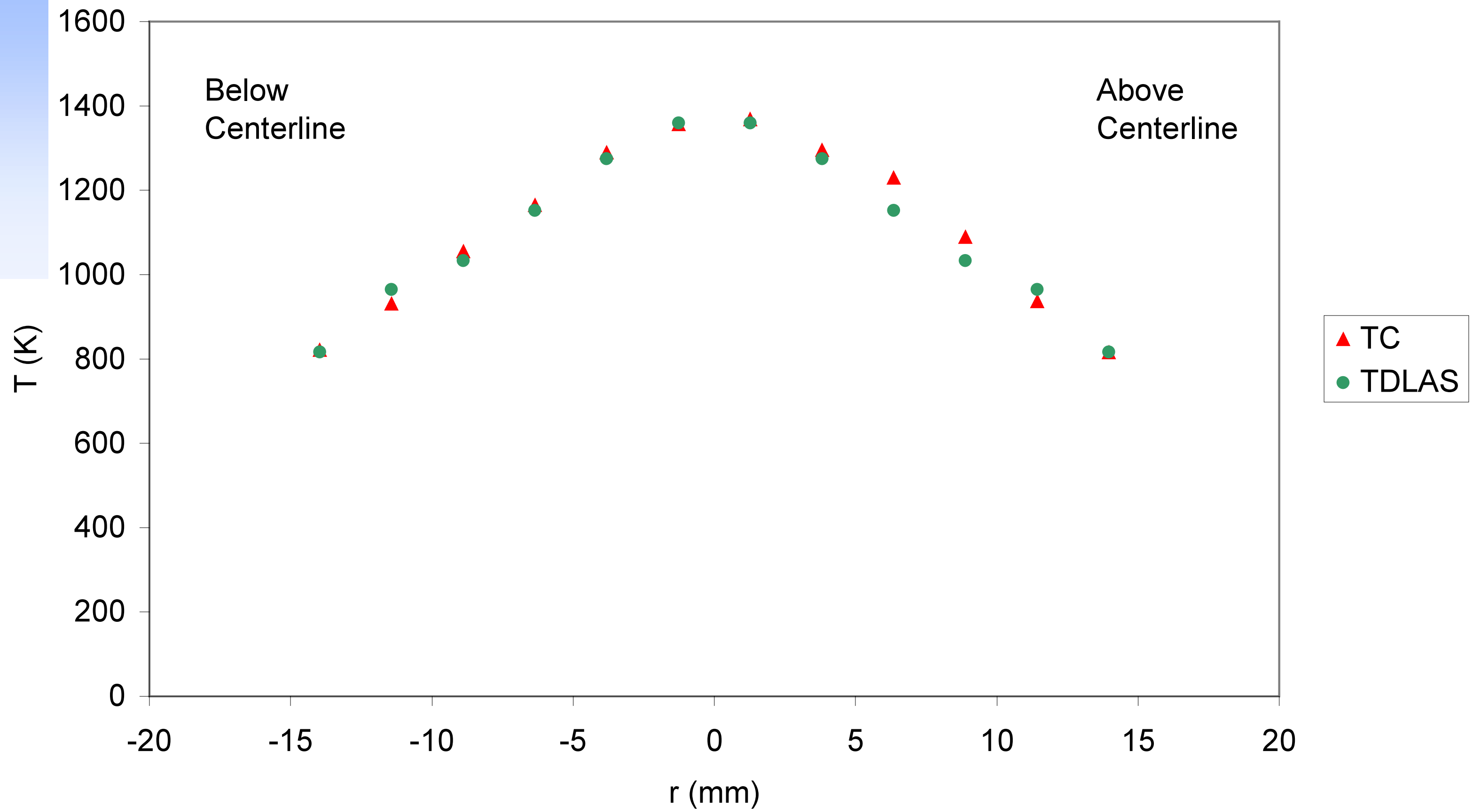
Shells of Constant Absorbance



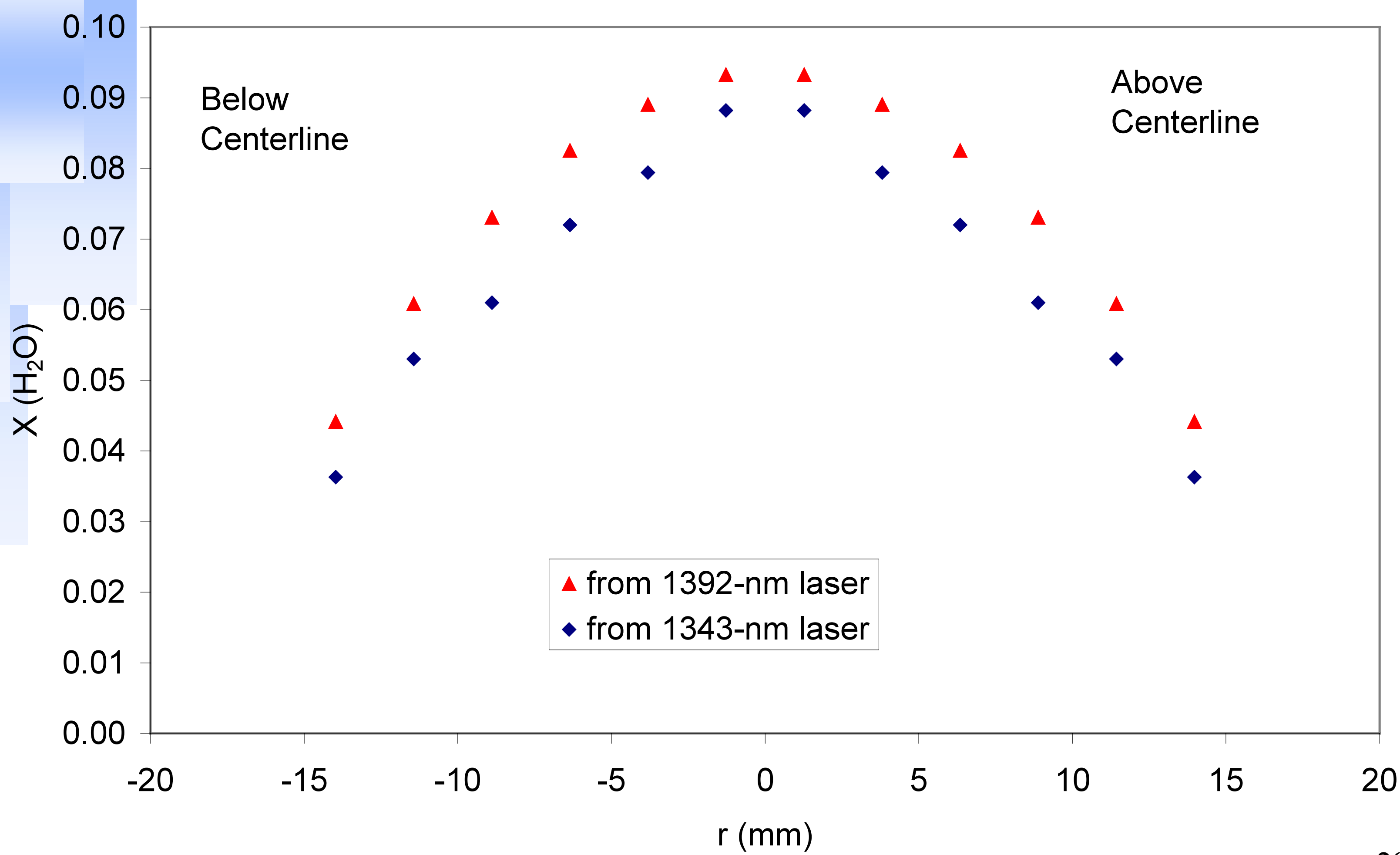
Calibration



Measured Temperature: TDLAS and TC



Measured H_2O Concentration



Conclusions

- A TDLAS system has been developed and calibrated for Real-time *in situ* measurements of T and X_{H2O} in industrial applications
- The system enabled measurements in the flame zone where thermocouples failed
- Data rates of 10 Hz were demonstrated, with potential for being greater
- TDLAS sensors may help improve efficiency in and reduce pollution from industrial burners.

Future Work

- Demonstrate measurements of T & X_{H2O} in an industrial spray jet flame, and in a low-NO_x staged-fuel combustor
- Incorporate additional species, including CO_2, CO, NO, etc.
- Develop lower-cost version of current modulation electronics for commercial use

Acknowledgements

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